ON-ORBIT PERFORMANCE OF THE BRIGHT TARGET EXPLORER (BRITE) NANOSATELLITE ASTRONOMY CONSTELLATION

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ABSTRACT

In 2013, the first three satellites of the BRITE-Constellation mission, believed to be the world's first satellite constellation dedicated to astronomy, were placed into orbit on two separate launches. To be eventually composed of at least six cooperating nanosatellites, BRITE-Constellation's mission is to perform a survey of the most luminous stars in the Earth's sky. In the push to observe ever fainter objects, these apparently bright stars, despite being prominent members our most familiar constellations, have been poorly studied and are not well understood. Typically massive and short lived, through their turbulent lives and via their especially violent deaths as supernovae, these stars dominate the ecology of the Universe and are responsible for seeding the interstellar medium with elements critical for the formation of planetary systems and organic life. Using three-centimeter aperture telescopes for differential photometry, BRITE-Constellation measures brightness variations, in two colours, at the milli-magnitude level, a precision at least 10 times better than what is currently achievable from ground based observations.

Comprised of nearly-identical 7-kg nanosatellites, BRITE-Constellation was designed by the University of Toronto, Institute for Aerospace Studies, Space Flight Laboratory (UTIAS-SFL) of Canada. Each of three countries, Austria, Poland, and Canada, funded two of the six satellites. Three of these satellites were integrated and tested in Austria and Poland under the guidance of SFL personnel, while the other three were built and tested at SFL. Through this international collaboration, the constellation boasts not just the smallest astronomy satellites ever flown, but also the first Austrian spacecraft and the first scientific satellites for Poland. As such, the mission has garnered a tremendous amount of public support and interest in all countries involved.

As a result of the inherent mass, volume, data, power and financial constraints, performing a mission of BRITE-Constellation's scope on the nanosatellite scale was particularly challenging. Not least among the challenges was the need to point the spacecraft with an accuracy and stability never previously achieved with a spacecraft so small. Enabled by advances in miniaturized technology, precise characterization and tuning of attitude hardware and novel estimation and control techniques, BRITE-Constellation is now pushing the nanosatellite performance envelope by achieving three-axis pointing at the sub arc-minute level, an advance which has helped ensure BRITE-Constellation will provide substantial scientific return on investment in the years to come.

This paper describes the goals, key design and operational challenges, on-orbit performance, and early scientific results of this cutting-edge mission.

1 INTRODUCTION

The origins of BRITE-Constellation can be traced back to the founding of the Space Flight Laboratory when, in 1998, SFL took on a leading role in the development of the Microvariability and Oscillations of STars (MOST) microsatellite mission. MOST's mission was to perform asteroseismology of solar type stars through the use of high-precision photometry (i.e. measuring brightness variations over time). Because atmospheric scintillation can easily mask minute variations in a star's brightness, even a small space-borne telescope can far exceed the photometric precision achievable from the ground. Despite its potential, MOST faced some significant challenges, not least of which was that staring at stars for weeks at a time required attitude stability far in excess of what had been previously accomplished with such a small satellite. As such, at the time of its launch in 2003, some in the spacecraft industry were still questioning whether such a mission could be achieved on the microsatellite scale. Still in operation, MOST went on to demonstrate arcsecond-level pointing (50x the mission requirement) and photometric precision more than 50x better than had ever achieved before. In the process, it demonstrated that small satellites were capable of far greater things than they were being given credit for.

At the same time MOST began enjoying such success, a burgeoning nanosatellite program was ramping up at UTIAS/SFL. After MOST's launch in 2003, the natural question became whether the expertise gained from the MOST mission could be leveraged to create a nanosatellite platform that was also suitable for precision astronomy. The question was put to the originator of the MOST concept, Dr. Slavek Rucinski, who realized that a nanosatellite could indeed fill another niche in the astronomical world. That is, in part due to the push to observe ever fainter targets, the brightest stars in the Earth's sky ($V < 4$) were poorly studied relative to their fainter counterparts. Many modern precision instruments with their increasingly large apertures were simply too sensitive to study them. Simply put, it was not only possible to do precision photometry of bright stars with a nanosatellite, it was in fact the *ideal* platform from which to study them.

The concept was further strengthened when Dr. Rucinski observed that the stars in the Earth's sky that are apparently bright also tend to be intrinsically bright. Intrinsically bright stars tend be a massive, which provided another niche that could be filled since, again, massive stars are poorly studied relative to other star types. Massive stars are of particular interest to many astronomers because they tend to lead short and turbulent lives and the most massive of them, those above eight solar masses, end their lives in supernovae. As such, through the stellar material and heavy elements they shed throughout their lives, massive stars tend to dominate the ecology of the universe and ultimately seeded it with the elements necessary for life as we know it. A study of massive stars was the perfect complement to the MOST mission and its study of solar-type stars.

The BRITE concept was born. But once again, there were questions about whether a spacecraft so small could achieve the pointing required for such precision science. With three BRITE satellites now in orbit and two entering their second year of operations, this paper describes how BRITE-Constellation is now doing for nanosatellites what MOST did for microsatellites a decade before.

2 CONSTELLATION DEVELOPMENT

In 2004 a concept study, funded by the Canadian Space Agency, established feasibility of the BRITE mission. In 2005 funding for BRITE was received from a seemingly unlikely source, the University of Vienna, where Dr. Werner Weiss, a member of the MOST Science Team had become very interested in the BRITE concept. Preliminary design of that spacecraft, dubbed UniBRITE, had only just begun when, in January 2006, the Austrian Space Agency (FFG) funded a second BRITE satellite, dubbed BRITE-Austria. Intended to be identical to UniBRITE, BRITE-Austria would be constructed and tested in Austria under the guidance and mentorship of SFL personnel.

With the expansion of the mission to two satellites, the science team began considering ways in which the science could be enhanced to make best use of the fact that multiple satellites would be launched. During the course of that investigation, the option of doing two-colour photometry without introducing unacceptable complexity or risk (e.g. moving parts, complex optics) became the enhancement of choice. As a result, two variants of the science instrument were designed, one for each satellite, with one focusing on the blue end of the spectrum (390-460nm) and the other on the red (550-700nm). The bandpasses of the filters were selected so that the number of photons collected by each instrument was roughly the same for the average bright star (~10,000K).

Since bright stars are scattered throughout the sky, the BRITE satellites were designed to be capable of observing any region of it for at least six months of the year (i.e. the period in which the solar exclusion angle is greater than 90°). With so many potential target fields, a single pair of satellites could neither hope to study any given target field all of the time (i.e. for the spacecraft's entire orbit) nor could it expect to observe all possible target fields in its lifetime (two years). That is, the mission lends itself well to expansion by the addition of more satellites, a fact which is complemented well by its low cost and rapid development time. As such, throughout the course of the design, integration and test of the Austrian BRITEs, pursuit of funding for a pair of Canadian BRITEs continued. But before Canadian support for the mission could be secured, and as the Austrian satellites were nearing completion, Poland joined the BRITE team in 2009 by funding an additional pair of satellites. To be managed in much the same way as BRITE-Austria, as a technology transfer program, the first Polish BRITE (later dubbed "Lem" in a national naming competition) would be a copy of the Austrian satellites, while the second ("Heweliusz") would use the same bus and instrument electronics, but carry a payload with Polish-designed optics. It was not until 2010 that funding for a pair of Canadian BRITE satellites was finally confirmed and BRITE-Constellation reached its present complement of six satellites, three red and three blue.

With BRITE-Austria representing the first satellite in history for Austria and Lem representing Poland's first scientific satellite (second satellite of any kind), excitement for the mission was understandably quite high with both nations taking the extraordinary step of commemorating their contributions, prior to launch, with national stamps (Figure 1).

Figure 1 – Austrian and Polish stamps commemorating their contributions to the BRITE-constellation

Now in its second year of operations, the BRITE satellites are believed to be the first nanosatellites dedicated to astronomy and, as a whole, BRITE-Constellation is believed to be the first orbiting astronomy constellation of any size, ever launched.

3 MISSION DESIGN

3.1 Operations Concept

BRITE observation scheduling is performed by the BRITE Executive Science Team (BEST). Twice per year BEST selects target fields based primarily on scientific merit, but with consideration of expected observability over the entire half-year campaign. The first step in setting up a new observation campaign is to acquire a full-frame payload image of the target-field while the spacecraft is in fine three-axis pointing. This image allows the BEST instrument scientist to confirm that the field orientation is correct and to determine the position of each star on the CCD.

With that knowledge, and knowing that fine three-axis pointing will hold the stars to their original locations, the instrument scientist defines a small Region of Interest (ROI) around each target star. To reduce data volume, for each exposure, only the ROIs are downloaded to the ground. For any given field, 15 or more ROIs may be defined depending on the number of bright stars of scientific interest in the field.

Since the scientific goal of BRITE is to acquire time-series photometry of stars, targets are imaged over a span of at least 15-minutes, every orbit, with images being taken at a cadence of six or more seconds, depending on the number of ROIs in the field (and hence the time required to process the data). Observations continue in this manner for approximately six months. That is, as long as a sun exclusion angle of at least 90 degrees can be maintained.

3.2 Payload Design

Each BRITE satellite carries a single refractive telescope designed specifically for its optical passband. Though the red and blue designs are slightly different in optical prescription, they are similar enough that, for the purposes of this paper, they can be treated as identical. The only exception to this is Heweliusz which, as noted in Section 2, uses a different optical design not covered in this paper.

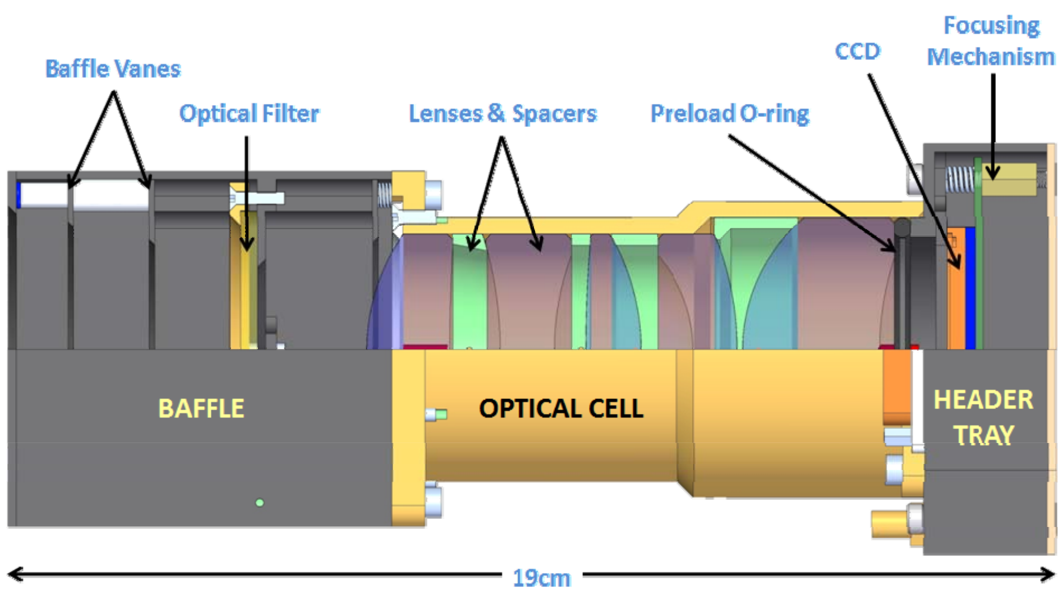

Figure 2 – Cutaway view of the BRITE telescope

Each BRITE telescope is composed of three modules, the header electronics tray, the optical cell and the baffle. The baffle includes the aperture stop as well as the optical filter. The optical cell houses five spherically-ground lenses and the spacers that position and align the lenses with respect to each other. The electronics tray contains the CCD header board, which includes the CCD and thermal control electronics. A cutaway view of the blue instrument can be seen in Figure 2.

Each of the three payload modules is almost completely self-contained. That is, each module can be assembled or disassembled on its own without having to integrate it with other modules. This modularity proved crucial at several points in the development and focusing of the first BRITE instruments. In addition to the three modules described above, the associated computing and CCD driver electronics are contained separately on the instrument on-board computer (IOBC), which is stacked with the other on-board computer (OBCs) on the satellite bus. This segregation was implemented to reduce payload size and limit heat dissipation (and hence self-heating) of the instrument itself.

As originally conceived the BRITE mission was to make use of a CMOS detector (IBIS4-14000). However, fairly early in the design of the mission, it was discovered that the IBIS4 suffered from severe Fabry-Pérot fringing, most probably caused by unevenness in the surface passivation layer of the detector. This fringing rendered the imager completely unusable for precision photometry and, after some research, information was uncovered that suggested that other CMOS imagers would be similarly afflicted. After a thorough search, a Kodak monochrome interline transfer CCD with microlenses was selected as the replacement. This CCD was chosen for its large pixels (9µm), low power, low readout noise and low dark current at room temperature, a feature which enabled it to be used without active or passive cooling.

The optical design is naturally telecentric, has an aperture of 30mm, a focal length of 70mm (focal ratio of 2.33) and a field of view (FOV) of 24°. This large FOV was selected to ensure at least three target stars were observable anywhere in the sky.

High precision photometry requires a defocused, smoothly varying point spread function (PSF) because it increases dynamic range and makes measurements less susceptible to wander-induced aliasing caused by inter and intra-pixel sensitivity variations and dead zones between pixels. While the goal was to have a Gaussian PSF with a FWHM of approximately 6 pixels, this proved difficult to achieve over the entire FOV. Hence, focal exploration was performed after the telescopes were assembled and an intra-focal position was selected that resulted in toroidal PSFs of approximately 8-pixel diameter. Further information on the BRITE instrument design can be found in [1].

3.3 Bus Design

SFL’s Generic Nanosatellite Bus (GNB) is an advanced 20cm cube, 7kg nanosatellite platform. Originally designed to support two missions (one of them BRITE) with very different requirements, the GNB offers 11W peak power generation, redundant 4.8Ahr energy storage, 1GB data storage, 2Mbps peak downlink rate, redundant 60MHz on-board computers, three-axis attitude determination and control and GPS capabilities. The GNB can therefore easily accommodate a wide variety of payloads and operational profiles with minimal modification to its core equipment complement. An example of six fully integrated GNB satellites covering four missions is shown in Figure 3.

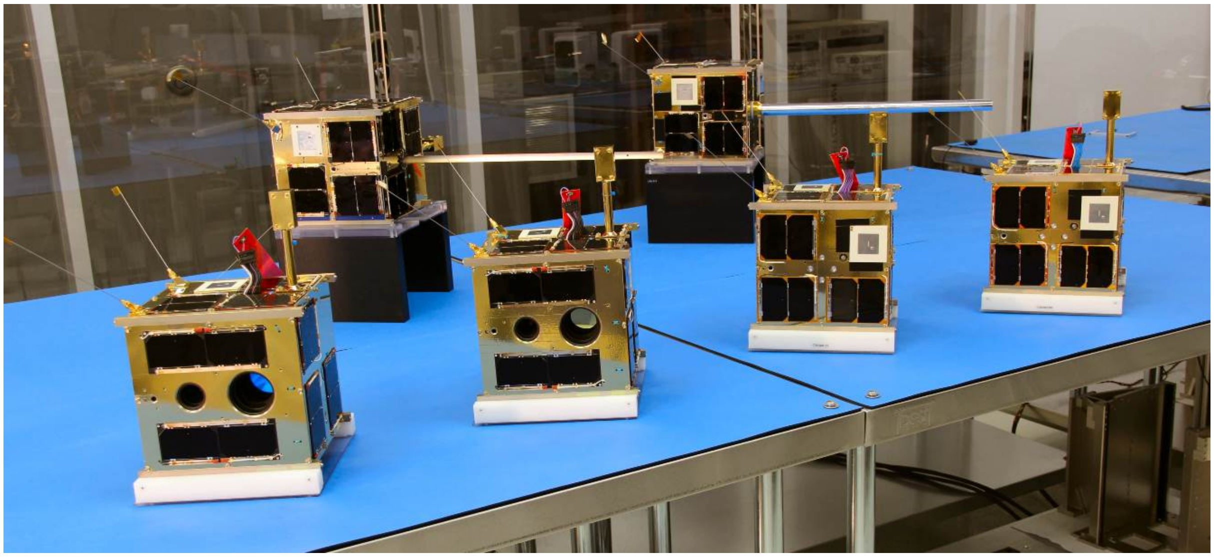

Figure 3 – BRITEs-Canada (front, left), CanX-4/-5 (front, right), EV9 (back, left), AISSat-2 (back, right)

4 ATTITUDE DETERMINATION AND CONTROL SUBSYSTEM DESIGN

In order to meet the photometric precision required by BRITE, the attitude determination and control subsystem (ADCS) needed to maintain a pointing stability of 78 arc-seconds (1σ) (as measured on the science instrument) over the entire six month imaging campaign. This stability translates into about 3 pixels on the payload detector. The duration over which the requirement applies implies not only a need for stability, but also repeatability, as the ADCS must re-acquire the target-field, returning the PSFs to the same pixels, each time the target comes into view after being occulted, or after imaging a different star-field earlier in the orbit. As such, the ADCS plays a significant role in the quality of the science. Such accurate pointing, on this scale of spacecraft, had never before been achieved.

The BRITE-Constellation ADCS is based on that of the GNB, the first of which, AISSat-1, launched in July 2010. AISSat-1 employed the baseline suite of GNB attitude hardware, including reaction wheels, magnetic torquer coils, digital sun sensors, a three-axis magnetometer, and a three-axis rate sensor, to provide sufficient pointing accuracy in eclipse. With this complement, AISSat-1 demonstrated pointing accuracy of better than 3^{o} RMS in sunlight [2]. Achieving the necessary arc-minute level pointing and stability would require augmenting the sensor suite with a star tracker, improving the control hardware with tuning, and updating the determination & control algorithms with novel approaches.

One reason that such accurate pointing had not yet been demonstrated on the nanosatellite scale was the lack of precision sensors suitably sized for such a mission with mass, volume, power and of course cost all being issues. Only in the last decade have high performance miniature star trackers entered the market, thus enabling missions such as BRITE. The two Austrian BRITEs, being the first two funded, are using the AeroAstro Miniature Star Tracker (AA-MST), which was the only suitable star tracker available at the time of procurement. Since then, the jointly developed Sinclair Interplanetary-Ryerson University-SFL ‘ST-16’ star tracker has been developed and is carried by the Canadian and Polish BRITEs.

Tests of the AA-MST were conducted prior to launch and 1σ error (or noise) was found to be 23” about the sensor transverse axes and 114” about boresight. The high boresight error is moderated by the fact that the science telescope and star tracker are co-aligned along the same body-axis, therefore, the error, projected onto a star near the edge of the payload FOV is only 24". The error levels of the star tracker were low, but still near the limit of the arc-minute level accuracy sought. The ST-16 star tracker offers substantial improvements over the AA-MST with error measured at 7" in each transverse axes, and 70" about boresight (resulting in 15" at the edge of the imager FOV).

Solution noise is only half the problem however; time-varying thermal misalignments between the star tracker and the imager must also be tightly limited to ensure that the stellar PSFs return to the same set of pixels throughout the imaging campaign. This was accomplished by mounting the payload and startracker to the same bracket at the center of the spacecraft, where temperature swings are minimal. Any residual bias can be calibrated-out on orbit.

Miniature reaction wheels are another example of enabling ADCS hardware that has only recently become available. BRITE-Constellation employs 30mNms reaction wheels as the primary means of actuation. These wheels were jointly developed by Sinclair Interplanetary and SFL in 2006/07 specifically to support GNB missions, including BRITE. Reaction wheel jitter is a common attitude disturbance that must be characterized and minimized when developing precision attitude control subsystems. Reaction wheel jitter has two chief sources, radial forces caused by rotor imbalance and torque jitter caused by non-idealities in the reaction wheel's drive electronics and control software. Since the Sinclair-SFL reaction wheels are individually balanced to a level of less than 0.5×10^{-6}kg·m, the anticipated error due to imbalance is less than an arc-second [3].

The greater source of jitter comes from non-idealities in the wheel drive electronics and control software resulting in the wheel imperfectly tracking the commanded torque. The mission required that the reaction wheels deliver torque with little error, in order to ensure that the effect of the wheel controller error would be limited to a few arc-seconds per ADCS control cycle. Initial testing revealed that the wheels, when subjected to a representative torque sequence, had jitter an order of magnitude greater than required. A fast Fourier transform analysis revealed the cause was a tracking error which manifested itself as a 6.5Hz oscillation, as shown in Figure 4 and Figure 5. The wheel control gains were subsequently tuned from the original set-points, resulting in significant control improvements, lower jitter, and essentially a white noise jitter density distribution.

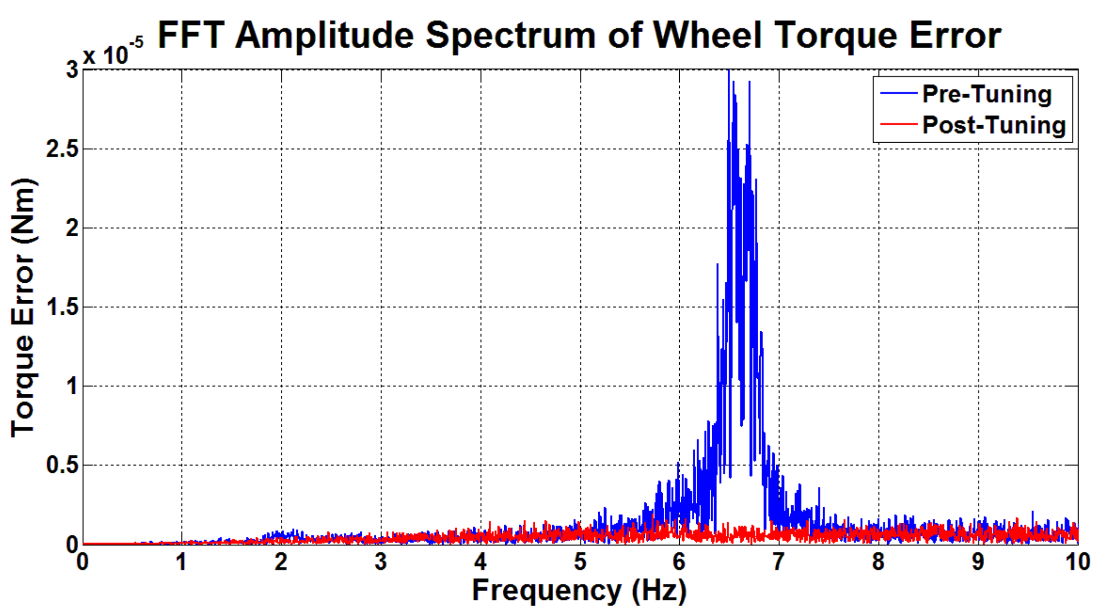

Figure 4 – Fast Fourier Transform of Wheel Controller Torque Jitter, Pre- and Post-Tuning

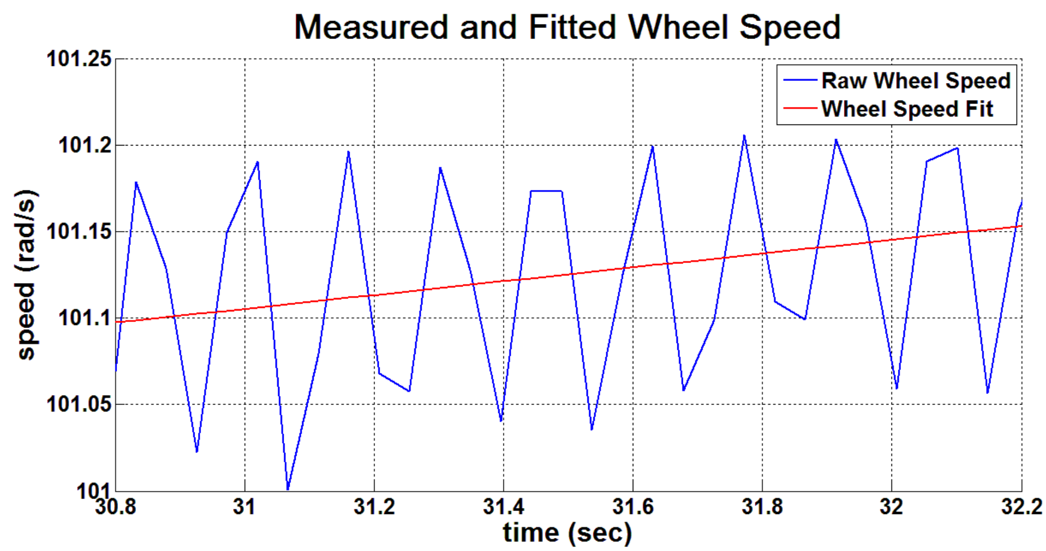

Figure 5 - Measured and Mean Wheel Speed of Pre-Tuned Wheel Controller Subject to Constant Torque

Equally important as sensors and actuators is the design of accurate estimation and control algorithms. SFL's On-orbit Attitude System Software (OASYS), is comprised of an extended Kalman filter (EKF) and a suite of control laws. OASYS was developed to be generic and, as such, has gained considerable heritage on SFL missions that require attitude estimation and active control (five spacecraft on-orbit over the last six years). OASYS itself is driven by the multi-threaded operating system, Canadian Advanced Nanospace Operating Environment (CANOE), which among other responsibilities, executes ADCS cycles at tightly-controlled fixed-cadences. An attitude cycle is comprised of a sensor-measurement collection period, execution of the estimation and control algorithms (i.e. OASYS), an actuator-commanding period, and a wait period. Attitude cycles on BRITE-Constellation are run at a period of 2500ms, which is dictated by the relatively slow AA-MST, which takes 1300ms to 2000ms to return a solution.

The EKF operates recursively, in real-time, on sequential noise-corrupted measurements to arrive at a statistically optimal estimate of the state variables defining the system. This is carried out over a two-step prediction (or state propagation) and sensor-update process. The on-board state estimator is a "cascade-EKF", which means that the sensor-update steps are conducted sequentially, in the order that the measurements are received. The spacecraft estimator is configured into coarse- and fine-estimation modes, with coarse mode using the magnetometer and sun-sensors, and fine mode using the star tracker exclusively. In fine estimation, a typical sequence of the EKF begins with an "a priori" state variable propagation from the time of the last calculated state, up to the point of the star tracker measurement time stamp, followed by a star-tracker sensor-update step, and a final "a posteriori" variable propagation to the approximate time of actuator commanding.

Due to the accuracy of the star tracker, the estimate of the state variables at the time of the sensor-update is very good. However, since the star tracker requires 1300ms to 2000ms to arrive at a solution, the a posteriori propagation distance is very long, causing a very large error, if not managed very well. As this propagation step estimates the state at the time that control outputs are calculated, the resulting errors can have an amplified impact on overall pointing errors since, with poor determination, control torques may be applied in non-optimal directions and magnitudes. A posteriori propagation errors are a function of state model fidelity, accuracy of the telemetry populating the model variables. Errors, therefore, are minimized by strict accounting for each of the terms in the propagated state equation.

The state equation of an attitude extended Kalman filter is a seven element vector, describing the time rate of change of the body-rate and quaternion vectors, through Euler's equation and the quaternion kinematics relationships, respectively. Therefore, the terms of interest to be characterized and accounted for include wheel, magnetorquer and disturbance torques, spacecraft and wheel inertias, measured wheel rates, and the spacecraft attitude state itself.

Of all the terms, disturbance torques are most important to characterize for precision pointing and, on BRITE, the dominant disturbance is magnetic. Since an accurate estimate of the residual magnetic dipole is hard to acquire on the ground, and since the dipole of ferromagnetic materials will change over time under the presence of the Earth-field, a novel alternative technique was formulated. The spacecraft three-axis pointing controller is a proportional plus integral plus derivative (PID) controller. In a well-tuned PID controller the integral term will track steady-state pointing errors, which are the net spacecraft disturbance torques. Therefore, instead of analytically calculating the disturbance torques, the integral term of the three-axis controller is fed into the state equation during the propagation step. As the integral controller will track steady-state error over time, the disturbance torques would be accurately estimated, thus improving estimation error. The simulated disturbance torques and the value of the three-axis controller integral term are plotted in Figure 6, showing a very good correlation.

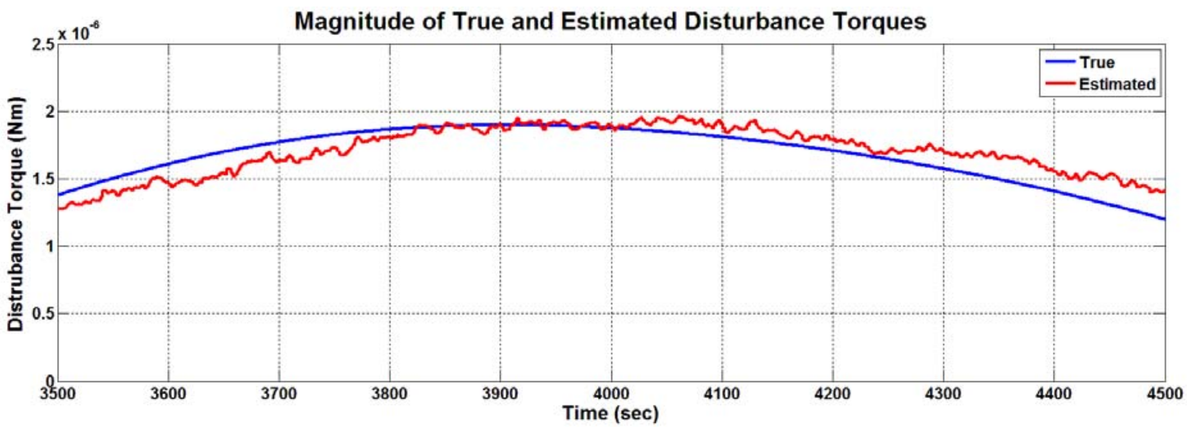

Figure 6 - True simulated and integral-term estimated disturbance torque magnitudes

Beyond this, measures were taken to reduce error in the other state equation terms. The spacecraft inertia was measured in-house through an accurate horizontal pendulum, to an error of less than 5%. The wheel torque fed into the state equation was the OASYS commanded (which is valid as the wheel delivers torque with little error, as described above), as opposed to calculating torque which would result in high-error from finite-differencing noisy wheel speed telemetry. Momentum-management of the wheels was disabled in fine-pointing to improve propagation error by zeroing the commanded magnetic torque, thereby eliminating any error that would have otherwise manifested through uncertainty in applied current and measured magnetic-field.

Through implementation of these sensors, actuators, control and determination software, the fine pointing accuracy of BRITE was simulated to meet requirements. On Austrian BRITE satellites, which carry the AA-MST, the pointing error was expected to be under an arc-minute, rms, or approximately 2-pixels, with the requirement being 3 pixels. A plot of a simulated projected star on the imager array over the course of a 15-minute observation is shown in Figure 7.

As discussed earlier, the Polish and Canadian BRITE satellites will fly the Sinclair ST-16 tracker, which offers substantially better accuracy with a RSS determination error of 23" as opposed to 52" for the AA-MST star tracker. Its time-to-solution is also lower, being only 500ms, instead of

1300ms to 2000ms, therefore significantly reducing the a posteriori propagation time. Equally important is the fact that the unit also estimates body-rates accurately, therefore, offering full observability over the state and reduced rate-errors during propagation. With the ST-16 star tracker, the Canadian and Polish BRITEs are expected to point with a better accuracy and stability than the Austrian BRITEs, which already have been routinely meeting requirements (see Section 6.1).

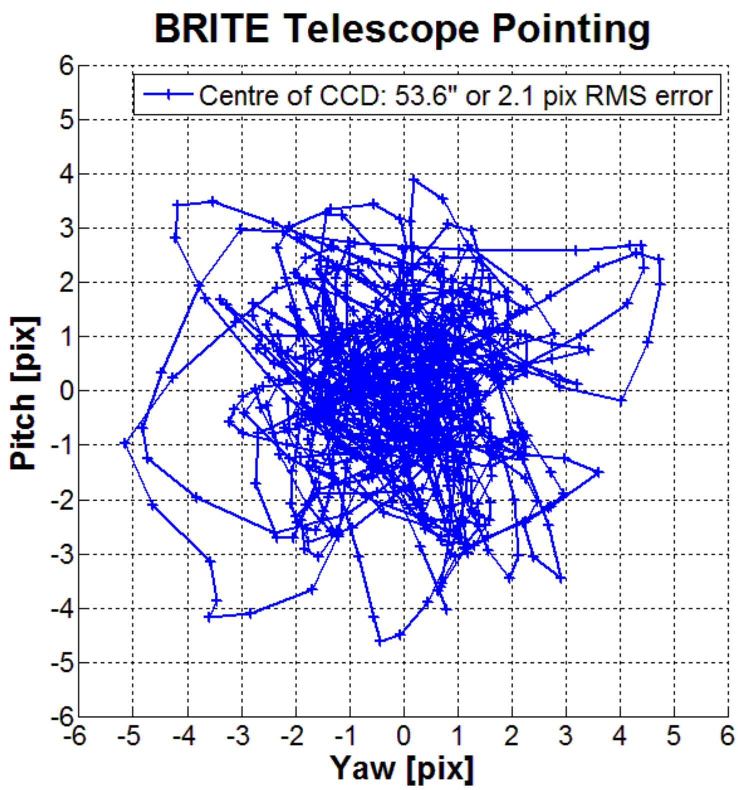

Figure 7 – Simulated BRITE Telescope Pointing Performance with the AeroAstro Miniature Star Tracker. Note, pixel pitch is 26 arc-sec/pixel.

5 COMMISSIONING

5.1 Launch and Early Operations

The first two of six BRITE constellation nanosatellites, UniBRITE and BRITE-Austria, were launched aboard an Indian Polar Satellite Launch Vehicle (PSLV) on February 25, 2013. The first BRITE-Poland satellite ("Lem"), was launched nine months later on a Russian Dnepr rocket. The Austrian BRITEs were placed in a 785 km sun-synchronous dawn-dusk orbit, with the Polish satellite in a 600 to 900 km ecliptic polar orbit with a current local descending node of 09:30.

Due to the locations of the BRITE Earth stations, initial acquisition of all spacecraft occurred hours after launch. Initial telemetry indicated a fully successful and healthy delivery into orbit. The satellites were commandable and responsive. The power systems were operating as expected, with expected levels of power generation observed. The thermal state of the spacecraft was in line with thermal model expectations. The main housekeeping computers were healthy, storing telemetry, handling command requests and generally ready to support higher levels of operations.

Due to the fact that the BRITE spacecraft are based on SFL's Generic Nanosatellite Bus (GNB), commissioning of the core hardware complement was conducted at an accelerated pace. Coarse three-axis pointing was achieved approximately two weeks after launch, after which focus shifted to functionality needed for fine pointing. A few notable hurdles were encountered and overcome before regular science operations were achieved. These challenges are described in the following subsections.

5.2 Coarse Three-Axis Pointing Error and On-Orbit Magnetometer Calibration

Coarse-estimation three-axis pointing does not use the star tracker, however, a mode exists in which the star tracker quaternions can be used to quantitatively assess the performance of the sun-sensor and magnetometer-based coarse pointing design. The hardware and algorithms that are used for coarse-pointing have been demonstrated in past SFL missions to achieve better than five degree pointing performance. Despite that, initial evaluations of the Austrian BRITE performance indicated poorer accuracy with periodic pointing error (having a period of a quarter orbit) in the range of 10°.

Given the fairly well defined period, a comparison of the error was performed against both position and magnetic vectors in the inertial frame. As expected, a correlation was found with the pointing error frequency being double the twice-per-orbit flip of the magnetic vector (see Figure 8). The pointing error is greatest and least, approximately when the North/South field strength is at a minimum and maximum respectively. Given this result, the source of the error was deemed to be magnetic in nature, possibly related to magnetometer calibration and an on-orbit recalibration was performed.

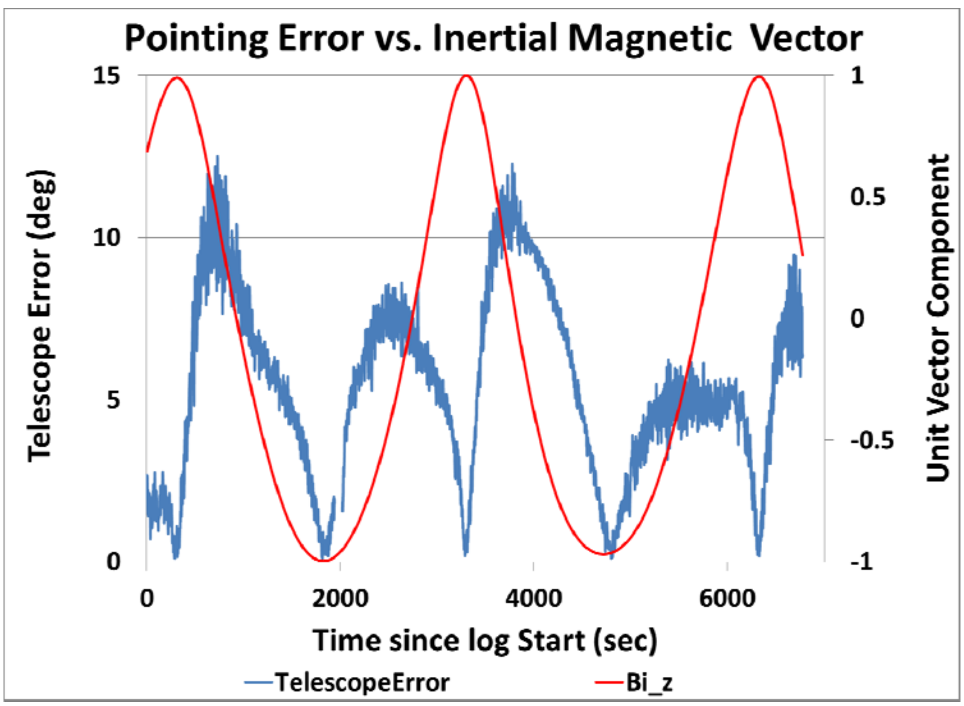

Figure 8 - Pre-magnetometer calibration coarse pointing telescope pointing error, and Z-component of inertial magnetic field vector, Bi.

The basis of the on-orbit magnetometer calibration was to use a least-square estimator to fit the coefficients of a linear model to transform the raw magnetometer signals into the true field. In this case, the true field was obtained by calculating the inertial magnetic field vector from the Inertial Geomagnetic Field Model (IGRF), which in turn is computed by calculating the spacecraft inertial position vector from the Standard General Perturbation Satellite Orbit Model 4 (SGP4), using a TLE and time input. The inertial magnetic vector is then rotated to the satellite frame, using the star tracker calculated inertial-to-body frame quaternion. As such, this true field is naturally subject to errors, notably the inherent error in the IGRF model, SGP4 model, TLE accuracy, time stamp accuracy, and any alignment biases between the star tracker and body-frame. The net error was, nevertheless, expected to be much smaller than the five degree accuracy sought, and likely within a degree.

The calibration was run a data from a single orbit. As a metric of the accuracy of the calibration, the magnitude of the field from the calibrated and true field were plotted together, as shown in Figure 9, yielding a good correlation. Following the calibration, the angle between the calibrated and true fields were computed, with the result indicating near co-alignment. Following this initial calibration, coarse three-axis pointing was retested and, though an oscillating error still existed, the magnitude was reduced to less than five degrees Figure 10, which is more than suitable for the BRITE mission.

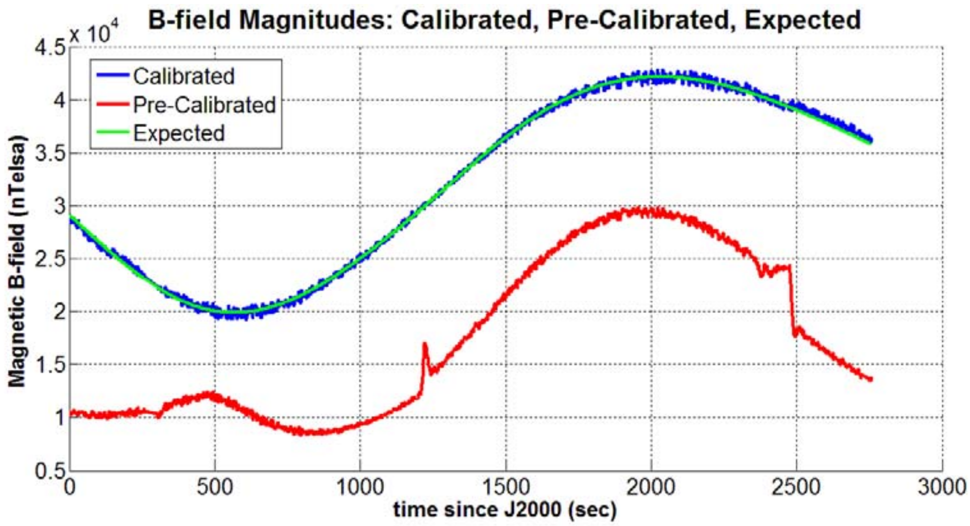

Figure 9 – Measured magnetic field, before and after calibration, relative to the expected magnitude.

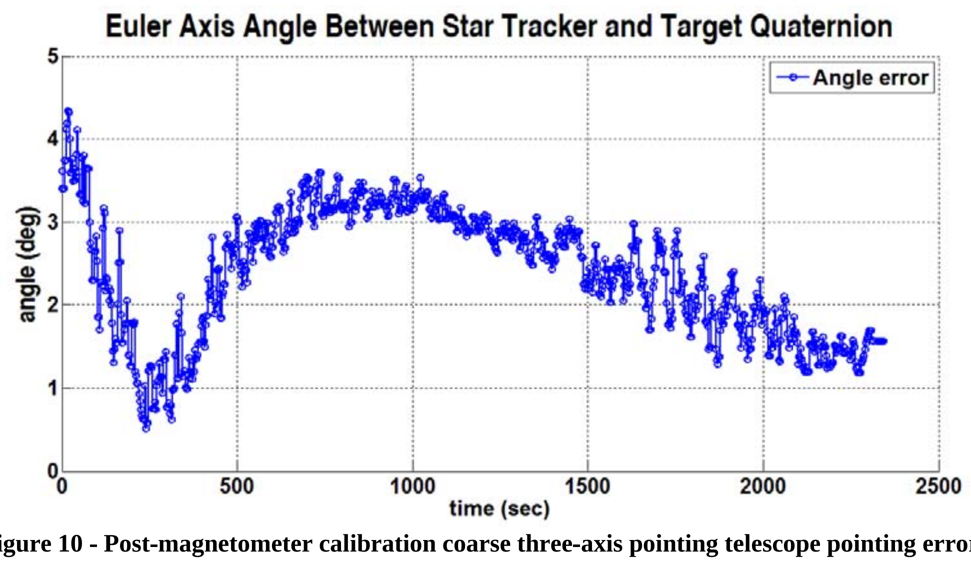

Figure 10 - Post-magnetometer calibration coarse three-axis pointing telescope pointing error

5.3 Aero Astro Miniature Star Tracker

Commissioning the AeroAstro Miniature Star Tracker (AA-MST) was a challenge. Early in commissioning, basic telemetry checkouts, such as current, voltage, and the output of the sensor's built-in-self test were found to be nominal. Despite that, initial attempts to acquire quaternions were not successful. The sensor has several customizable settings (with suggested defaults) and a parametric study was conducted to cover the likely settings-space, also proving fruitless. To eliminate stray-light from the sun, the spacecraft was oriented with the sensor in the anti-sun direction, for the majority of tests. Given the spacecraft are in a dawn-dusk orbit, this also generally resulted in reasonably large exclusion angles to the earth's horizon. Tests on numerous targets ranging from pre-selected science commissioning field targets to targets which maximized the earth exclusion angle were also performed.

Through all of this testing, though the star tracker had a very poor success rate, it did produce a very good rate of quaternion generation on some targets. Once a critical number of successful targets were obtained and the targets were plotted on a Lambert Projection of the sky, it became evident that the star tracker was only generating quaternions reliably when it was pointed at fields near or within the galactic plane, presumably due to the high-star density there. This result was puzzling since the AA-MST had been designed to have nearly complete sky coverage and, to date, remains unresolved.

Despite the coverage limitation imposed by the AA-MST, the mission is largely unaffected, since the vast majority of targets of scientific interest reside in the galactic plane. Those targets that are of interest but are not within the galactic plane can instead be studied by the Polish and Canadian BRITE satellites, whose S3S startrackers are known not to suffer such limitations.

During the course of commissioning, it was also found that the star tracker was imposing a fairly constraining exclusion angle to earth's horizon, which turned out to be up to 60^o, far from the quoted 25^o. While this exclusion angle is quite large, operations optimizations have minimized its impact on day-to-day planning and total observation time per orbit is still significantly beyond mission requirements.

Finally, it was also found that the AA-MST is highly sensitive to transits through the South Atlantic Anomaly (SAA). Reliably, the star tracker would stop producing quaternions upon entering the SAA. Depending on the declination of the target star field, this constraint can result in significant reduction in observation time during SAA-transit orbits. Again, however, operations optimizations, have resulted in observations spanning the minimum required time, per orbit.

5.4 Radiation Effects on CCD Imager

Approximately one month after launch, upon collecting the first full frame images from the Austrian BRITE spacecraft, it was observed that the images contained warm columns (increased bias compared to a typical background), and hot pixels (higher signal levels than surrounding pixels) not present before launch. Figure 11 shows a sub-section of an image obtained with the UniBRITE CCD after launch, which contains a warm-column, several hot-pixels, and as a point of comparison, two stars, to demonstrate how they can be easily distinguished from the hot pixels.

In subsequent weeks a number of images were obtained with both satellites in order to characterize the nature of the features in the images. Using images of similar temperatures but taken many weeks apart, it was concluded that the number of features was increasing with time but at a rate low enough that it is not expected to degrade science performance within the mission lifetime.

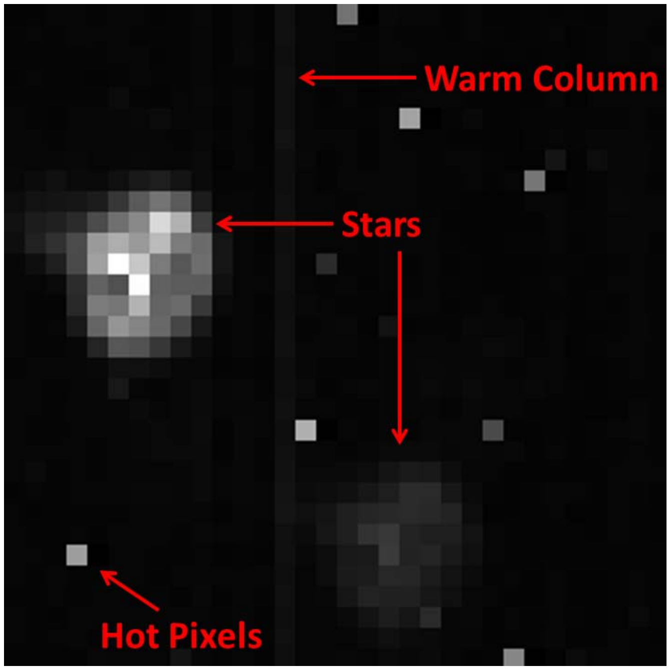

Figure 11 – Section of an image taken with the UniBRITE CCD 7 months after launch . In addition to stars, the image contains columns with higher signal levels and increased number of hot pixels.

The new data also strongly suggested that radiation damage was the cause for what was being observed. This theory was later confirmed through high-energy proton testing of an engineering model CCD. Radiation testing was not performed prior to launch because it was already known that CCDs were susceptible to radiation damage and, with the time and facilities available, it would have been impossible to use the test results to predict on orbit performance in any meaningful way. Hot pixels were assumed to be something that the science data processing algorithms would have to deal with eventually, the only surprise was how quickly the degradation happened.

Knowing that the rate of radiation damage was higher than anticipated gave incentive to try to improve the situation for the BRITE satellites still on the ground. The probability of a high-energy particle impacting the CCD is a function of how much material the particle must pass through before reaching the CCD. The CCD resides in the payload header tray (Figure 2), which itself is only millimetres away from the external surface of the spacecraft. Hence, on one side of the CCD, there is only about 3.5mm of aluminum to attenuate the radiation while in all other directions much greater shielding is realized. As such, it was decided that the most effective solution not requiring significant redesign of already built and tested spacecraft was to replace the back aluminium cover of the header tray with a tungsten version. This change has since been implemented on BRITE-Canada and is expected to reduce the total CCD's dose of 10-100MeV protons by a factor of approximately 2.75, thereby substantially slowing the degradation of the imager.

Despite these measures, all six BRITE satellites will need to deal with both hot pixels and warm columns throughout their lives. On the warm columns front, analysis of the collected data showed that they were an additive effect and could easily be subtracted out of the images. As such, an on-board processing mode has been added to calculate the column medians in each column of interest. Those medians are then downloaded along with the photometric data so that they can be subtracted on the ground during processing. For hot pixels, due to the small amount of attitude wander, static hot pixels are relatively easy to identify, even when they overlap with stars. Science data processing algorithms are now in place to detect them autonomously and remove them from the data. To further enhance the accuracy of the data processing algorithms, off-target observations (having no stars in the region of interest) are scheduled periodically so that all pixels in the region of interest can be better characterized.

In addition to better shielding, cooling of the CCD can also be used to help mitigate the effect of the radiation damage since at lower temperatures the column and pixel effects are much less pronounced. Hence, both the Polish and Canadian BRITEs have biased their thermal control measures toward the cold end of the spacecraft operational range. Should any more BRITE satellites join the constellation, ways to modify the design to passively cool the CCD will be investigated.

6 DEMONSTRATED PERFORMANCE

After a six and eight month commissioning period for UniBRITE/BRITE-Austria, respectively, by late 2013 both satellites were regularly observing one of the mission's primary science fields, the Orion Constellation. By March 2014 Orion had moved too close to the sun to be observed and the first observation campaign for the mission was considered complete. With that milestone achieved, it was possible to assess the performance of the mission with the two most significant outcomes at this stage being the demonstrated fine pointing performance, and the quality and quantity of the science data returned by the system.

6.1 Fine Pointing Attitude Stability and Accuracy

The performance of fine-pointing was investigated using high cadence star-field images taken by the spacecraft telescope. Shown in Figure 12 is a plot of the motion of the centroid of a stellar PSF, over a 15-minute observation, near one of the vertices of the imager field of view. The red circle represents the 3 pixel (78 arc-sec) requirement, and the green circle is the RMS error, demonstrating that the performance is well within requirements, and in line with simulation results.

Looking at pointing performance over a longer term, BRITE instrument scientist Rainer Kuschnig of the University of Vienna, compiled UniBRITE imager data to assess the wander of a target star (Eta Orionis) over a span of 40-days. The result is Figure 14 and Figure 14, which plots the cumulative X and Y pixel positions of the centroid. As expected, the data appears more or less Gaussian, since a large source of error is the star tracker noise, which is also Gaussian. The standard deviation of the X-axis and Y-axis are 1.44 pixels (37.4 arc-sec) and 1.42 pixels (36.9 arc-sec) respectively, resulting in an overall RSS of the standard deviation of 2.0 pixels (52 arc-sec). Hence, from field acquisition to re-acquisition, the star returns to the same set of pixels, and the observed pointing stability is about 2.0 pixels (1σ), better than the requirement.

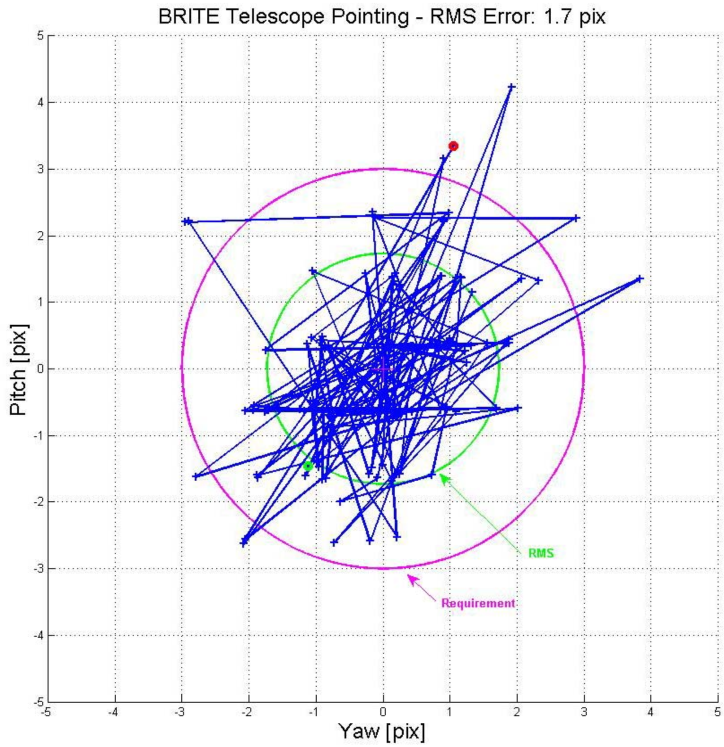

Figure 12 - On-Orbit Fine Pointing Performance of UniBRITE Spacecraft. Note, pixel pitch is 26arc-sec/pixel.

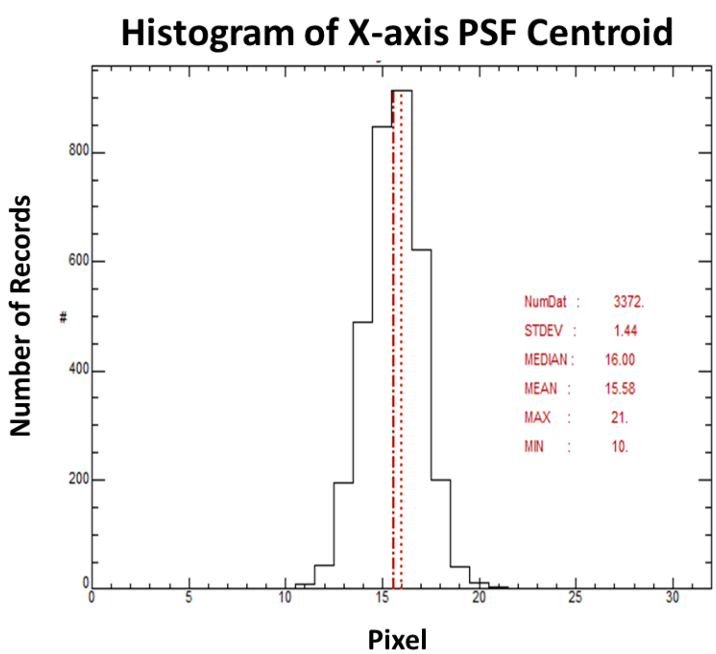

Figure 13 - Histogram of Star PSF centroid position on the X axis of telescope imager over 40 continuous days of observation on UniBRITE (courtesy of Rainer Kuschnig, University of Vienna)

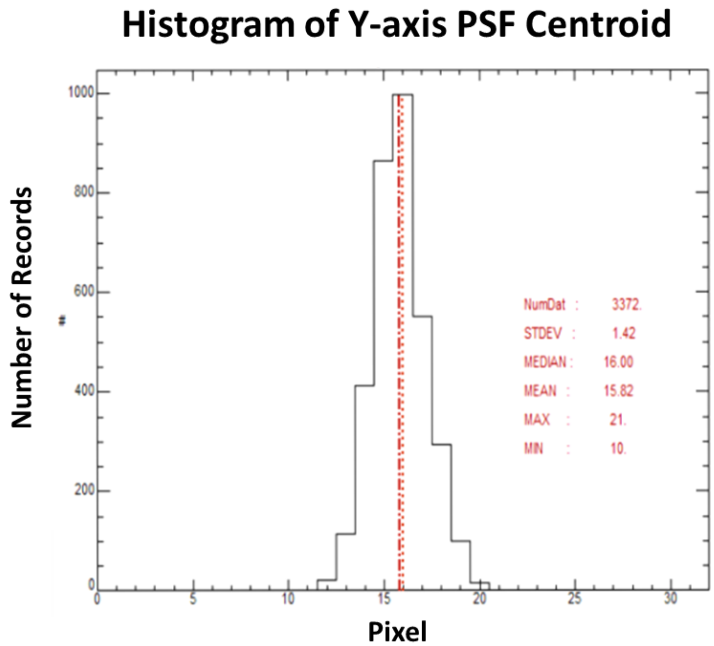

Figure 14 – Histogram of Star PSF centroid position on the Y axis of the telescope imager over 40 continuous days of observation on UniBRITE (courtesy of Rainer Kuschnig, University of Vienna)

6.2 Science Data Quantity

Throughout the course of the Orion and Centaurus campaigns, engineers have made steady improvements to procedures and software to increase uptime and efficiency. As a result of those efforts the spacecraft are now observing each and every orbit with >95% reliability. Time coverage of target fields has increased from 15 minutes/orbit (the mission requirement) to over 30 minutes. The number of ROIs has doubled, from the requirement of 15, to 30. And, though the mission requirements call for the study of stars with V<+3.5, BRITE is currently observing stars as faint as +4.5. As the performance of fine pointing has been reliable and repeatable, the size of the ROIs have been reduced from 32 x 32 pixels to 28 x 28 pixels, reducing the data volume by nearly a quarter. At the same time downlink capabilities have been steadily enhanced to the point where UniBRITE is now averaging in excess of 30MB/day of science data through the Toronto ground station alone, more than 15 times the mission requirement. In total, more than 80,000 data sets spanning 15 stars were collected for the Orion constellation.

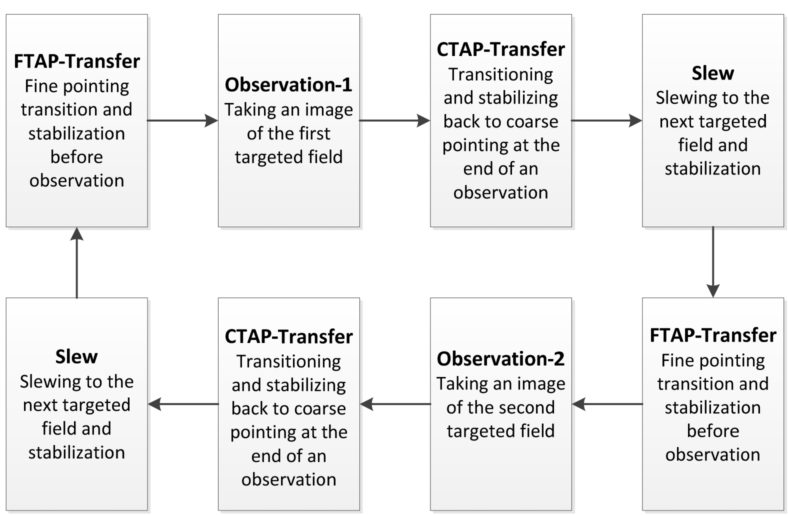

Figure 15 - Sequence of events for observation of two targets per orbit

Finally, though originally designed to image one target per orbit, operators have successfully experimented with observing two fields per orbit and, if targets are carefully selected with widely spaced observation windows, it may even be possible to image three fields. Observing more than one field per orbit has the potential to greatly increase the number of targets observed and hence the scientific return of each spacecraft. Figure 15 illustrates a typical operations sequence for two targets, assuming that the spacecraft is already coarsely pointed at the first target. Note, in the figure, CTAP and FTAP are acronyms for coarse and fine three axis control respectively.

6.3 Science Data Quality

UniBRITE commenced routine science observations of the Orion star-field in October 2013. Starting in December, BRITE-Austria joined UniBRITE on the campaign providing the mission's first two-colour photometric data. Conveniently, in late 2013, MOST was also observing Eta-Orionis (a quadruple system with an eclipsing binary pair) and, for a time, all three spacecraft were performing simultaneous observations. Through the simultaneous observations with MOST, the team was able to confirm that, to first order, that the quality of the BRITE data was as good as expected. A minimally post-processed light-curve of Eta-Orionis, taken by UniBRITE and with a binary transit clearly evident, is shown in Figure 16.

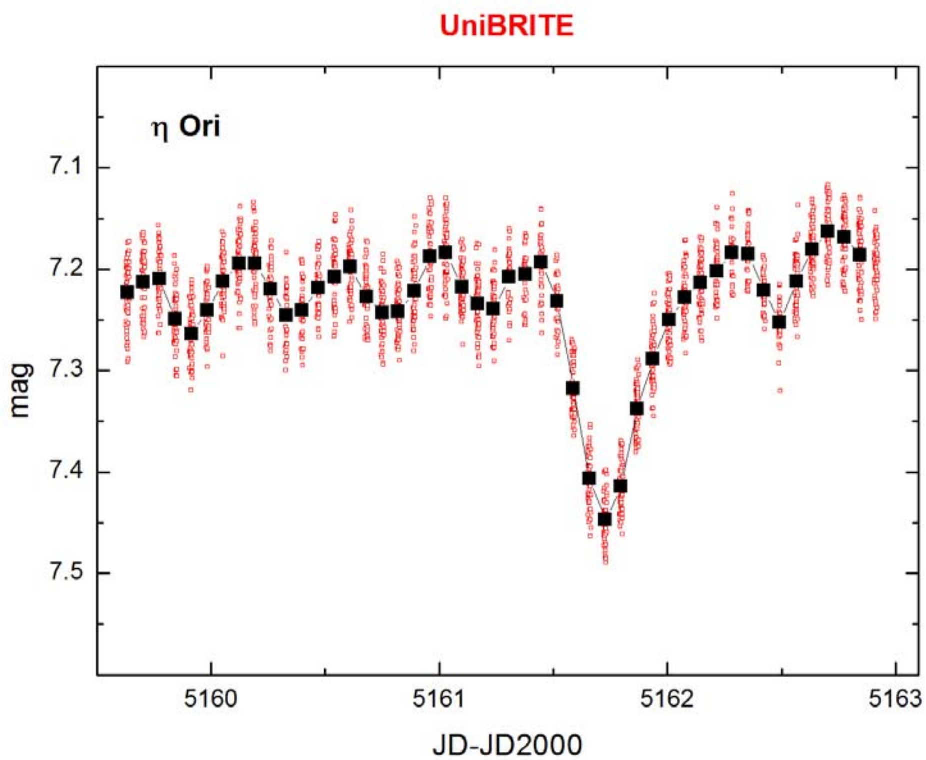

Figure 16 – Light curve from Eta-Orionis, from UniBRITE data (image courtesy of Rainer Kuschnig, University of Vienna)

At the time this paper was submitted, the full Orion dataset is still being analyzed, but preliminary analysis has already shown that the data is of excellent quality and the promise of two-colour milli-magnitude precision photometry of bright stars will be realized. Meanwhile, the Austrian spacecraft are now well into their second primary science campaign on the constellation Centaurus. When the primary field is not in view, the spacecraft are now observing a secondary field (the constellation Sagittarius) each orbit as well. At the time of submission, the first Polish BRITE satellite ("Lem") is completing commissioning, and will soon join the observation campaign with the Austrian spacecraft.

7 FUTURE OF THE BRITE-CONSTELLATION

With the remaining three BRITE satellites launching in mid-2014, the entire constellation is expected to be fully operational by the end of the calendar year. Lessons learned during the commissioning of the first three satellites should ensure that future satellites can be commissioned very quickly, with the goal of being fully operational and ready to collect science data one week after launch.

In addition to expansion of the satellite constellation, the network of ground stations supporting the constellation may also soon be expanding. Construction and testing of a station in Aruba is already underway. In Vancouver there are plans to upgrade the MOST ground station for compatibility with BRITE (essentially the addition of a UHF uplink).

In addition to adding ground stations, new ground station control software (called MUX) will soon be deployed that will enable more efficient use of the existing BRITE ground station network. To date each BRITE satellite has had a master station with operations from other stations occurring only rarely and with configuration and data sharing being handled manually if so. With the introduction of MUX, any satellite will be able to communicate seamlessly with any ground station with the downloaded data being routed over the internet. Even without adding new ground stations, this software upgrade has the potential to double the downlink capacity of a given satellite (if Graz and Warsaw were not almost co-located, the increase would be ever greater).

Finally, new spacecraft software is presently being deployed that will enable each spacecraft to operate in a "broadcast" mode when in view of the ground station. Combined with functionality that allows holes caused by dropped packets to be filled in parallel with the broadcast stream, this upgrade will ensure the downlink channel gets used to its maximum capacity. As a result, the 30-35MB/station/day that UniBRITE is now obtaining (more than 15x mission requirement already) could increase substantially in the near future.

On the science front, from very early in the mission development there was a desire to supplement BRITE observations with ground-based observations, particularly spectroscopic measurements. With the observing schedule for the next year currently being finalized these simultaneous observations are now also beginning to materialize and the first may even occur in 2014. The addition of simultaneous ground-based measurements has the potential to add an entirely new dimension to the scientific return of the mission.

Looking even further into the future, concepts for maximizing observation time on the spacecraft through onboard automation are also being explored. In such a scenario, rather than a ground-based operator conservatively scheduling observing times and expected availability windows, the spacecraft itself would monitor its orbital position and attitude state to decide on its own, in real-time, when conditions are suitable for payload data collection. Letting the spacecraft decide when to collect payload data not only has the potential to increase the percentage of science data that is good, but will also ensure the total amount of science data collected is maximized.

8 CONCLUSION

Three BRITE satellites are currently on orbit, and the remaining three will be launched in 2014. The commissioning of the Austrian BRITEs, being the first to launch, was complete by October 2013, and since then they have been routinely collecting science data, each orbit. The first field investigated, from October 2013 to March 2014, was Orion. Once Orion had set, the spacecraft moved on to observing the field Centaurus, while also observing secondary target field Sagittarius in tandem.

While commissioning of such a cutting-edge mission met with some hurdles, all now have been cleared, resulting in a quality of science generation which meets and exceeds both requirements and expectations. Although BRITE-Constellation has already swollen to a size not dreamed of when it was first conceived, the mission continues to garner interest in participation from other nations. Attracted by the enticing nature of the science, the success of the transfer programs with Austria and Poland and the relatively low-entry cost, to date, at least six other nations have expressed interest in contributing additional satellites to the constellation. In anticipation of future expansion, discussions are already underway on how those satellites can best be used to further enhance the science as the addition of BRITE-Austria did eight years before. At the top of the list is a BRITE satellite capable of observing in the UV, an addition which would push this already highly valuable mission into even new territory.

In short, BRITE-Constellation is a successful example of the capabilities of low-cost yet high-performance nanosatellites and is redefining what spacecraft of its size are considered capable of.

9 ACKNOWLEDGEMENTS

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